Simultaneous Aerodynamic and Structural Design Optimization (SASDO) for a 3D Wing

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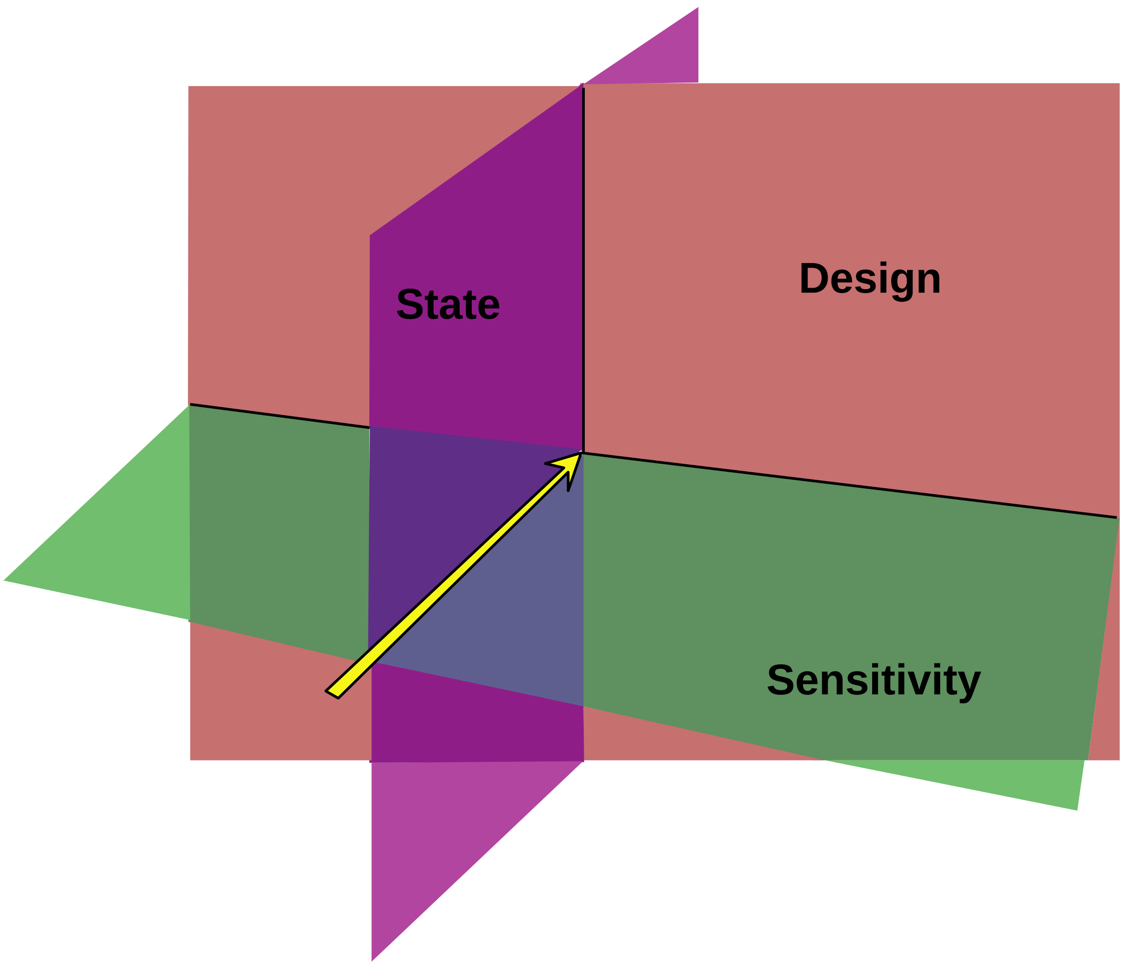
Motivation

- Multidisciplinary Design Optimization with high fidelity (nonlinear) PDE analyses
  - Loosely coupled discipline interactions
  - Use validated legacy codes
  - Minimize implementation issues
- Reduce computation cost from conventional optimization

Outline

- Conventional Approach
- Optimization Challenges
- SASDO Approach
- Process Implementation
- Application Problems
- Results
- Conclusions

Conventional Approach



$$\min_{\beta} F(Q,u,X,\beta)$$

subject to constraints

$$g_i(Q,u,X,\beta) \le 0, i=1,2,\ldots m$$

- β **design variables**
- X **computational mesh**
- Q **CFD flow variables (state)**
- u **FEM deflections (state)**

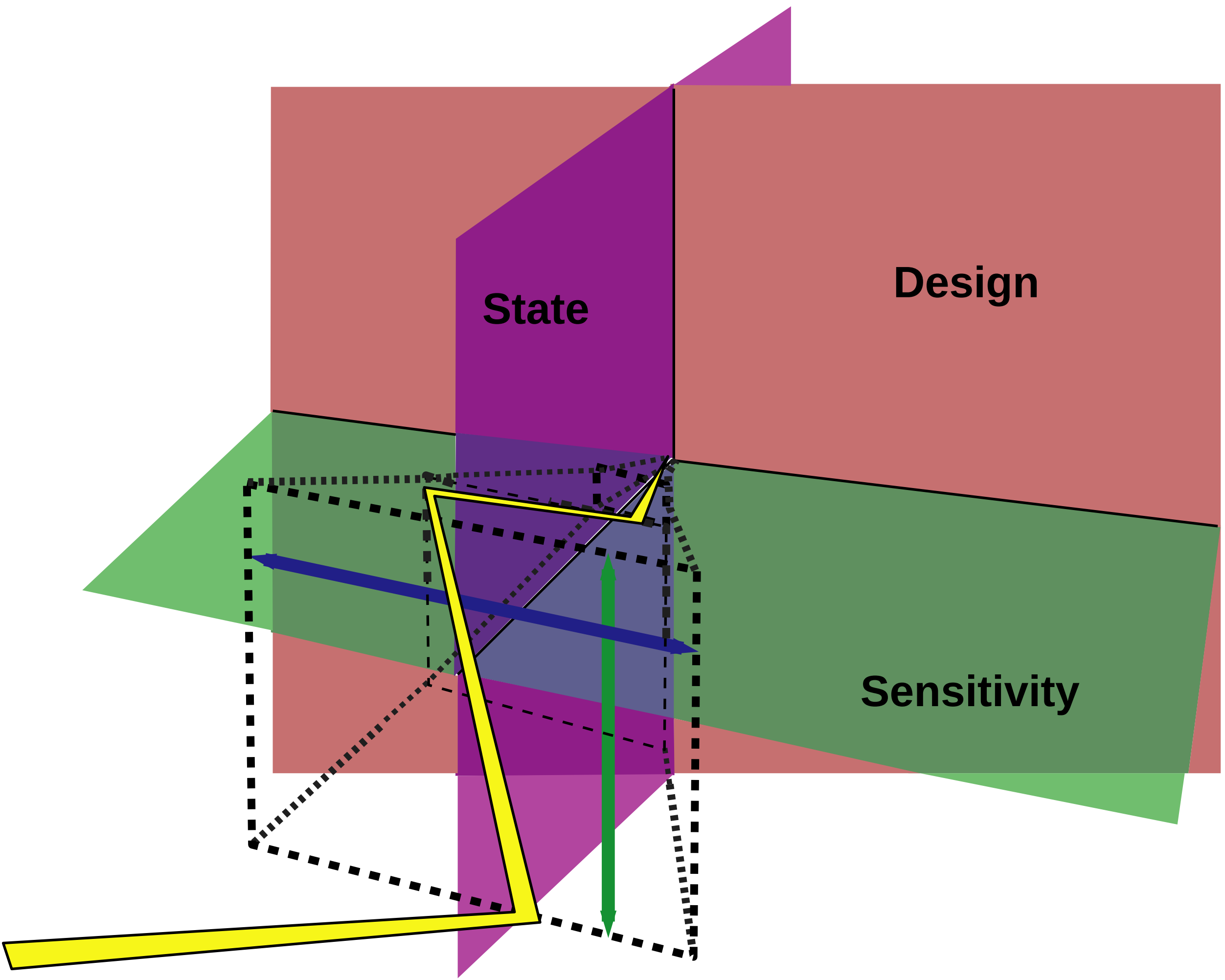
$\left.\begin{array}{l} Q\,(u,X,\beta) \\ u\,(Q,X,\beta) \end{array}\right\}$ **solutions of coupled aero-struct equations**

$\left.\begin{array}{l} Q' \\ u' \end{array}\right\}$ **solutions of coupled aero-struct sensitivity equations**

Optimization Challenges

- **Why SASDO?**
  - Minimize modifications to discipline analysis codes
  - Reduce the cost incurred by well-converged, iterative function and sensitivity analyses at non-optimal points in design space
- **How SASDO?**
  - Interleaf optimization updates with iterative discipline and system analyses
  - Require better convergence for function and sensitivity analyses as optimization progresses
- **Past SAADO**
  - Demonstrated for 1D, 2D, and 3D aerodynamic optimization (single discipline)
  - Demonstrated for 3D flexible wing shape optimization (two disciplines)
- **Present 3D SASDO goals**
  - Structural design variables added
  - Results which agree with conventional optimization
  - Computational cost less than conventional optimization

SASDO Approach



$$\min_{\beta, Q, u} F(Q, u, X, \beta)$$

subject to constraints

$$g_i(Q, u, X, \beta) \le 0, \ i = 1, 2, \ldots m$$

and

$$R(Q, X, \beta) = 0$$

$$K(X, \beta)\, u - L(Q, X) = 0$$

SASDO Approach

Partial convergence implies:

- **Approximate functions (state) and gradients (sensitivities)**

- **Infeasibility in early design steps**

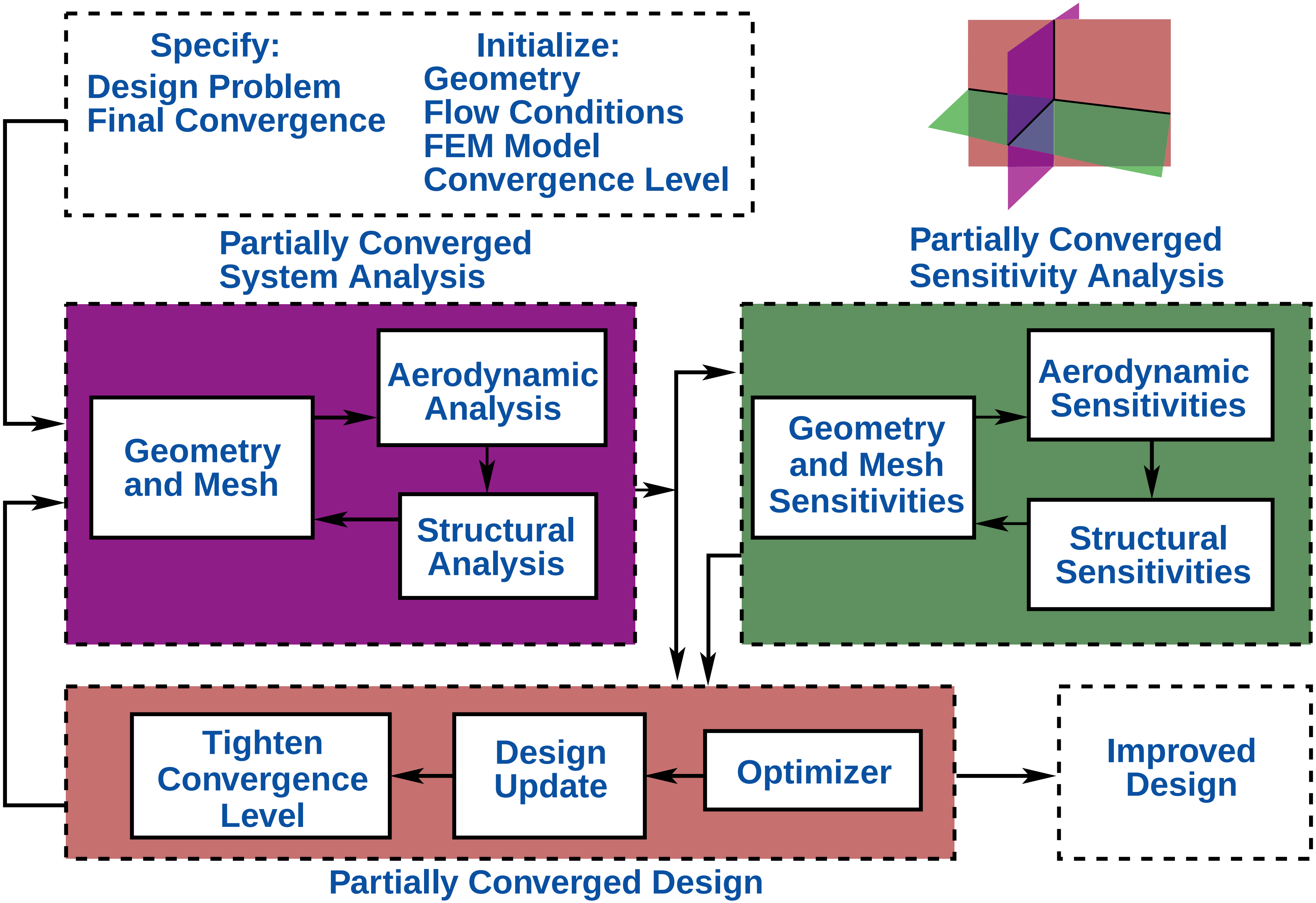
$$R\,(Q,X,\beta) \neq 0$$
$$K(X,\beta)u - L(Q,X) \neq 0$$

- **Contribution to reduction of design variable domain**

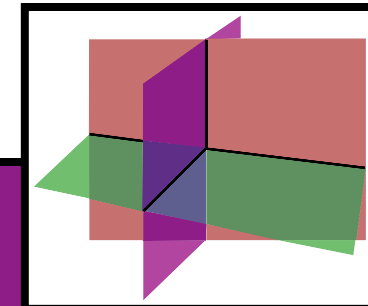
$$R + \frac{\partial R}{\partial Q}\Delta Q + \frac{\partial R}{\partial X}\Delta u + \left[\frac{\partial R}{\partial X}X' + \frac{\partial R}{\partial \beta}\right]\Delta\beta = 0$$

$$Ku - L - \frac{\partial L}{\partial Q}\Delta Q + \left(K - \frac{\partial L}{\partial X}\right)\Delta u$$
$$+\left[\frac{\partial K}{\partial X}u - \frac{\partial L}{\partial X}\right]X'\Delta\beta + \frac{\partial K}{\partial \beta}u\,\Delta\beta = 0$$

Process Implementation



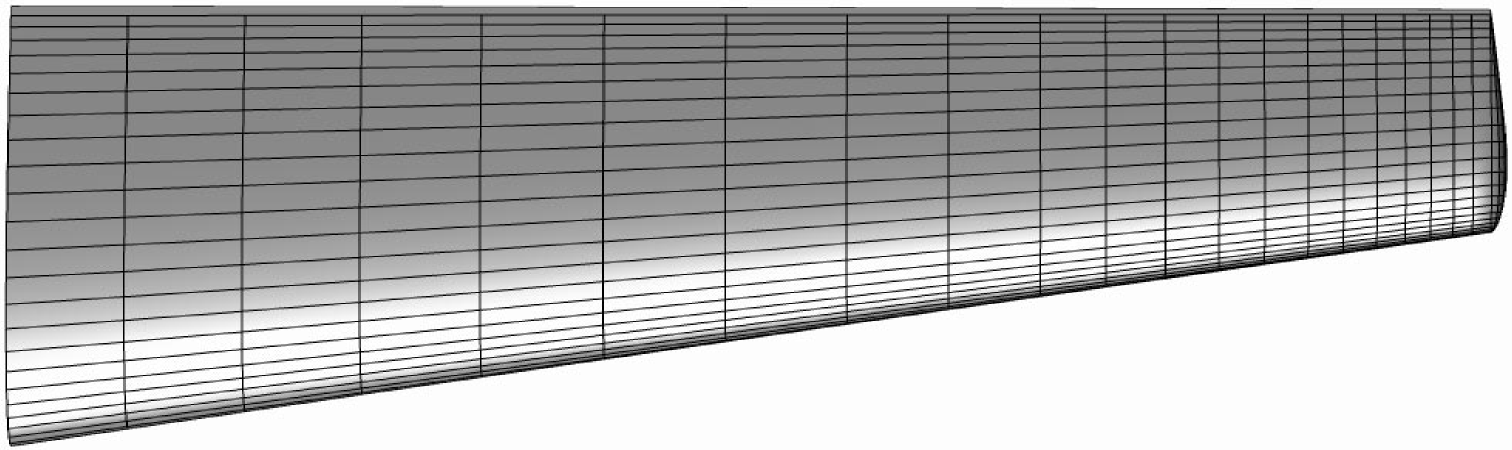
Process Implementation
Code Descriptions



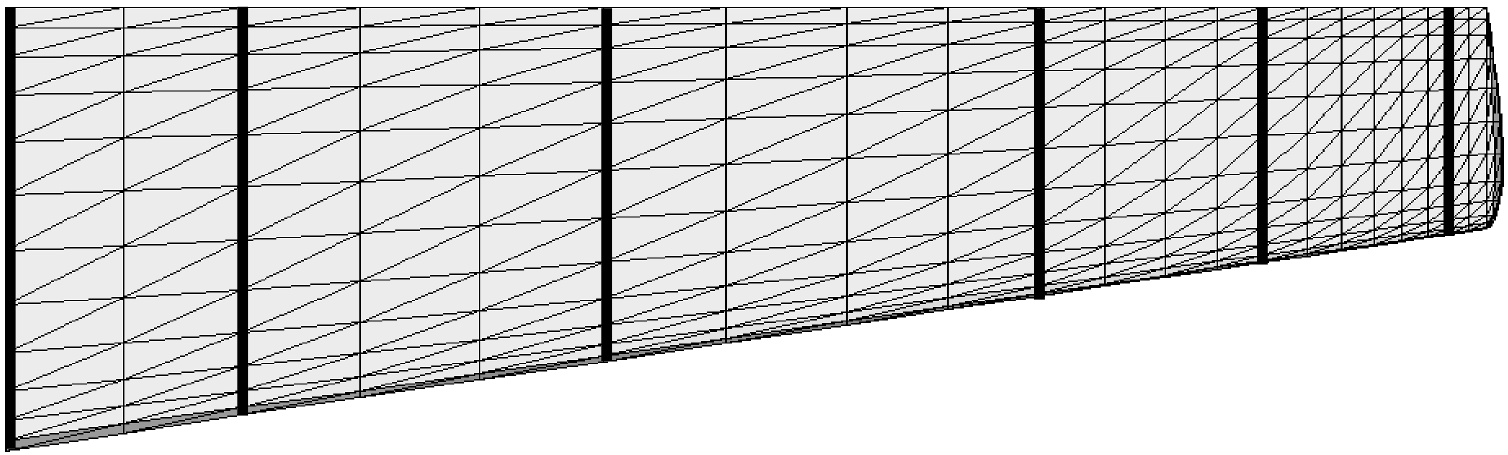
Code	Description
RAPID	Surface geometry generation Rapid Aircraft Parameterization in Design
CSCMDO	Volume mesh generation Transfinite interpolation of deformations
CFL3D	General structured mesh Euler or Navier-Stokes flow analysis; Euler used in this study
FEM	Finite Element Method linear structural analysis
	Sensitivity derivatives obtained by Automatic Differentiation of Disciplinary Analysis Codes
DOT	Sequential Quadratic Programming (SQP), Vanderplaats R&D, Inc.

Process Implementation
Computational Meshes

CFD mesh
C-O topology
73x25x25 volume
49x25 on wing



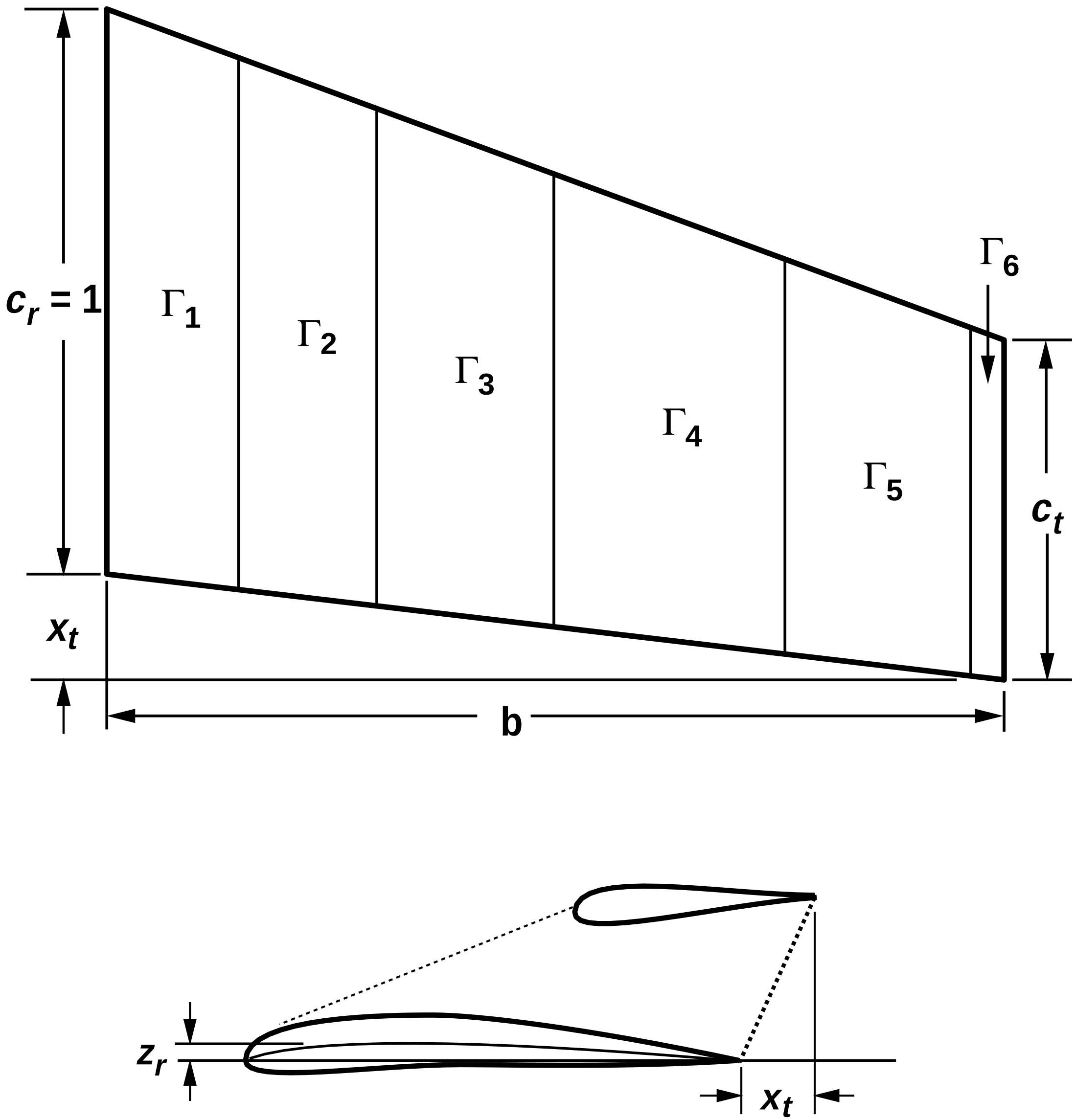
FEM mesh
3251 elements:
  1110 truss
  2141 CST
583 nodes



Application Problems
$M_\infty = 0.8$, $\alpha = 1°$

- Four design variables
  - Two wing planform (i.e., aero shape and structural geometry)
  - Two structural sizing
- Eight design variables
  - Three wing planform (i.e., aero shape and structural geometry)
  - Four structural sizing
  - One aero section camber

Application Problems
Wing Configuration and Parameterization



4 DV:
- zone 1 sizing, Γ_1
- zone 2 sizing, Γ_2
- tip chord, c_t
- tip setback, x_t

8 DV:
- 4 DV+
- semispan, b
- root camber, z_r
- zone 3 sizing, Γ_3
- zone 4 sizing, Γ_4

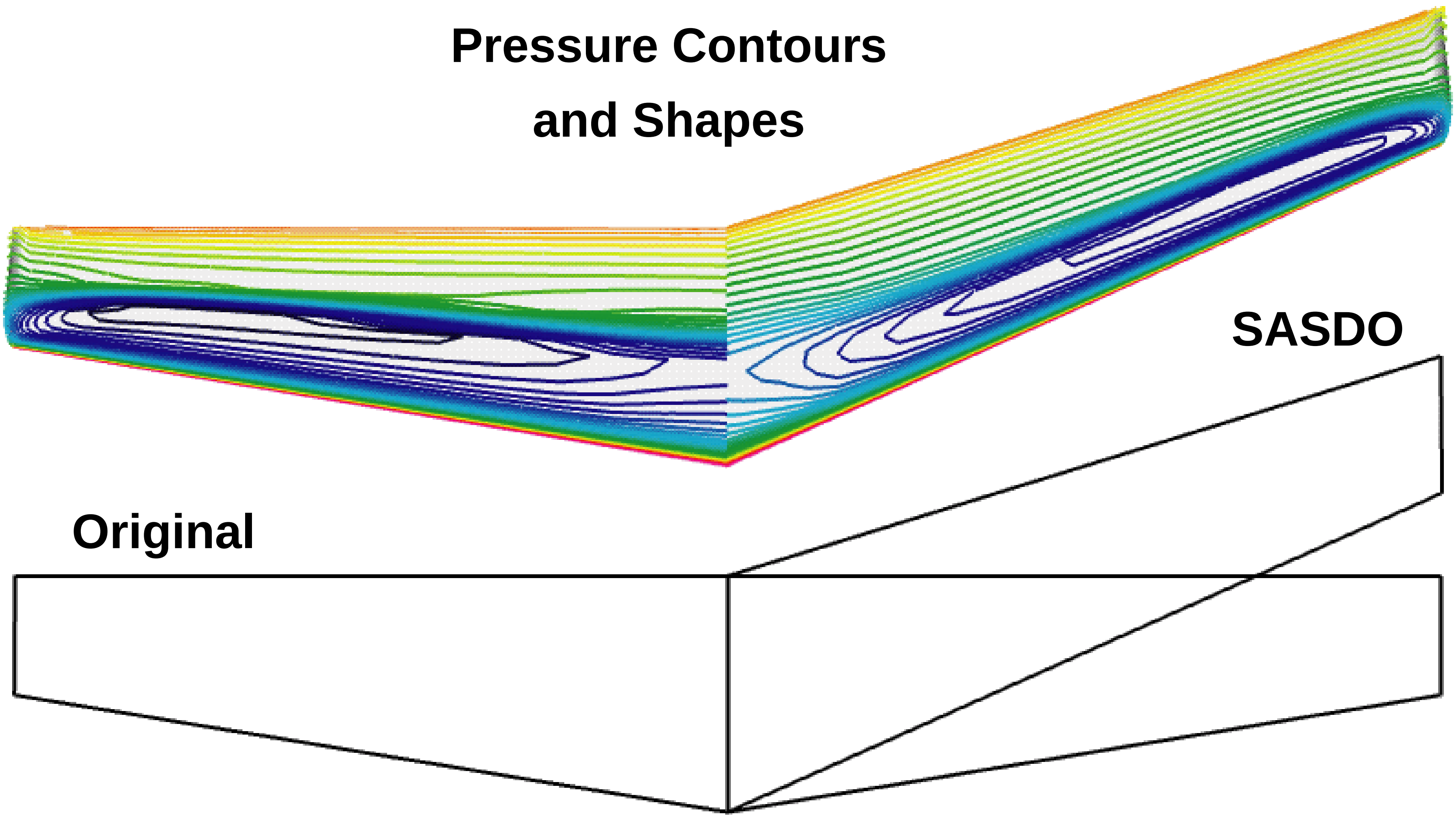
Application Problems
SASDO for a 3D Wing

- **Objective function: negative lift to drag ratio, –L/D**

- **Constraints:**
  - **minimum payload:** $C_L * S * q_\infty - W \geq L_{\mathrm{min}}$
  - **maximum compliance:** $\oiint p\, u \cdot ds \leq P_{\mathrm{max}}$
  - **maximum pitching moment:** $C_m \leq C_{m_{\mathrm{max}}}$
  - **minimum leading edge radius:** yes

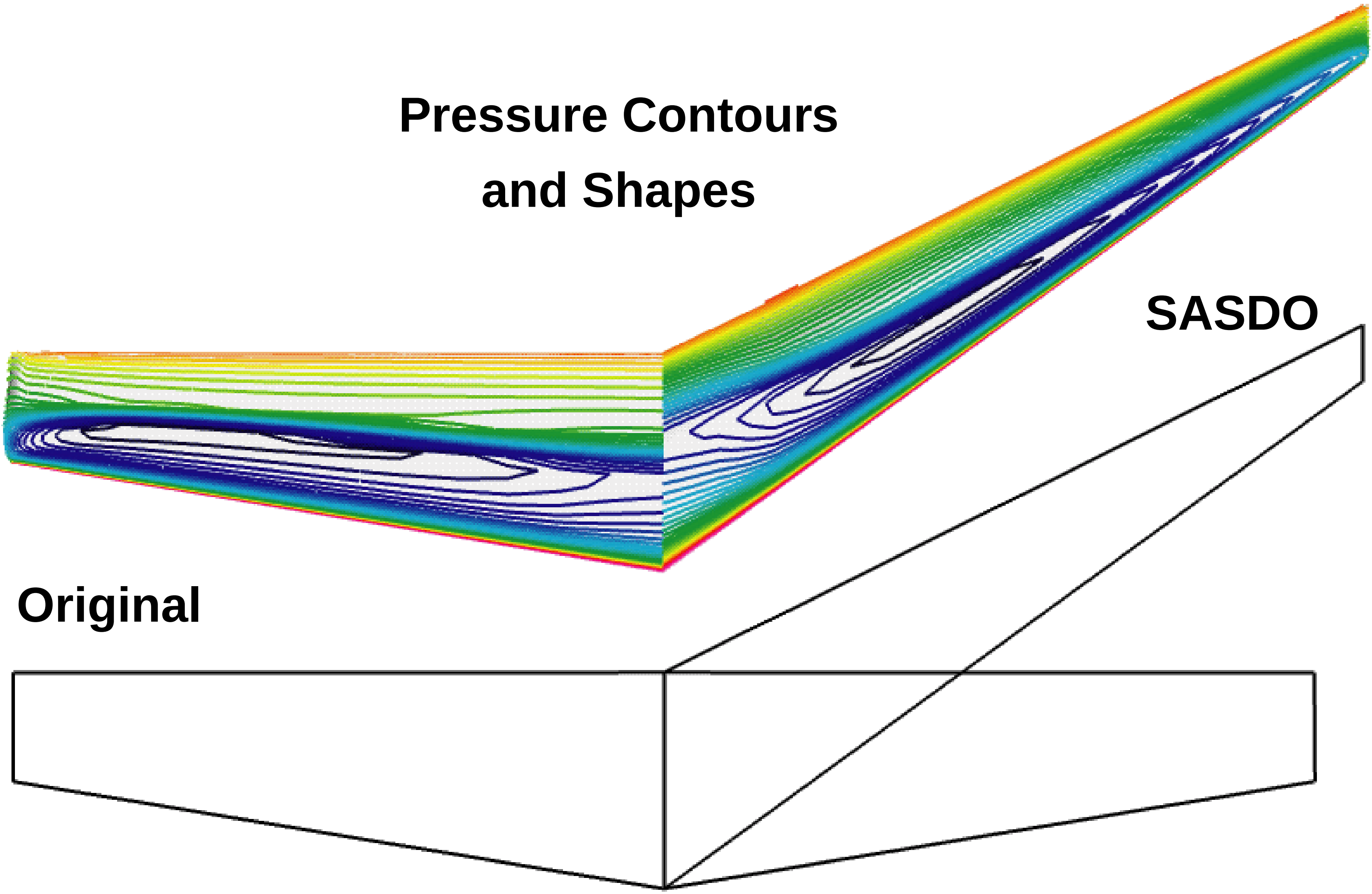
- **Design variables: planform, section, and sizing**

Four-Design-Variable Results
$M_\infty = 0.8$, $\alpha = 1^\circ$



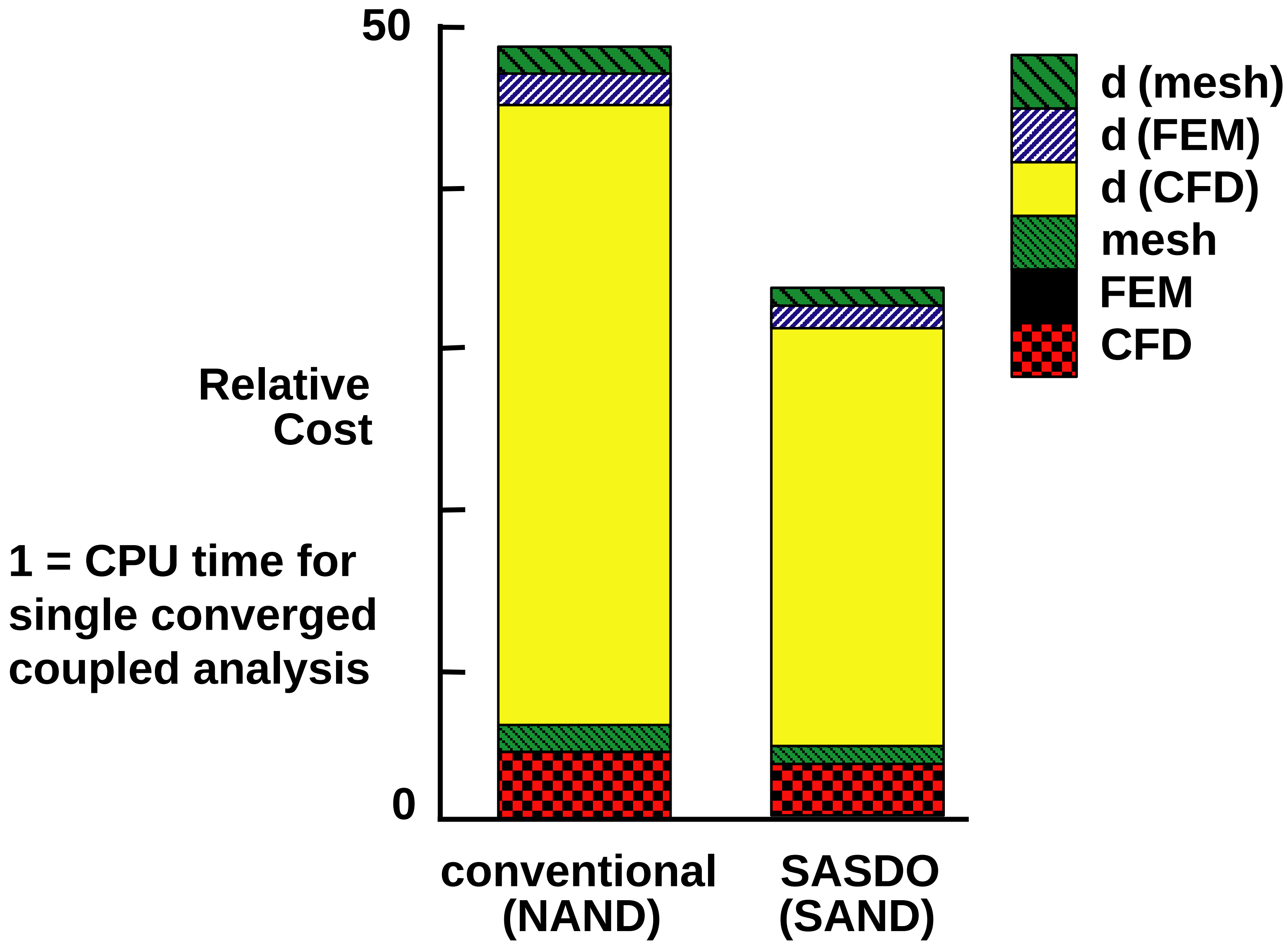
Eight-Design-Variable Results

$M_\infty = 0.8,\ \alpha = 1^\circ$

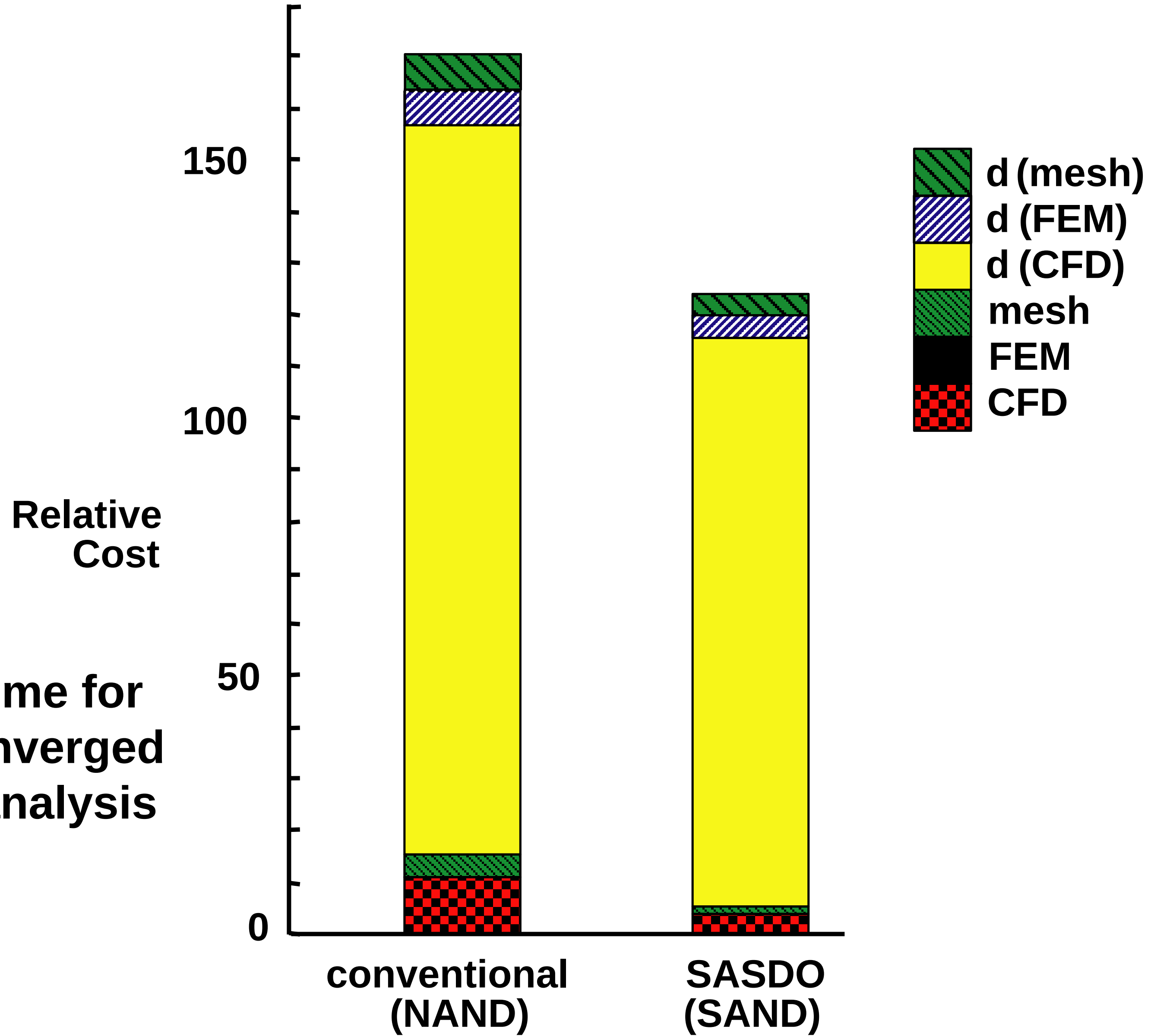


Four-Design-Variable Results

Computation Cost



Eight-Design-Variable Results
Computation Cost



1 = CPU time for single converged coupled analysis

Conclusions

- Initial 3D wing SASDO results obtained, demonstrating feasibility for dual simultaneity
- SASDO finds the same or similar local minimum as conventional optimization technique
- SASDO requires few modifications to the function and sensitivity analysis codes
- SASDO can be computationally more efficient than conventional gradient-based optimization techniques
- Gradient computation times dominate SASDO

Open Questions

- Gradient cost
  - adjoint approach for loosely coupled analyses?
  - code (compiler) optimization for AD code?
  - other approximations or methods?
- Optimizer control
- Sensitivity analyses error control

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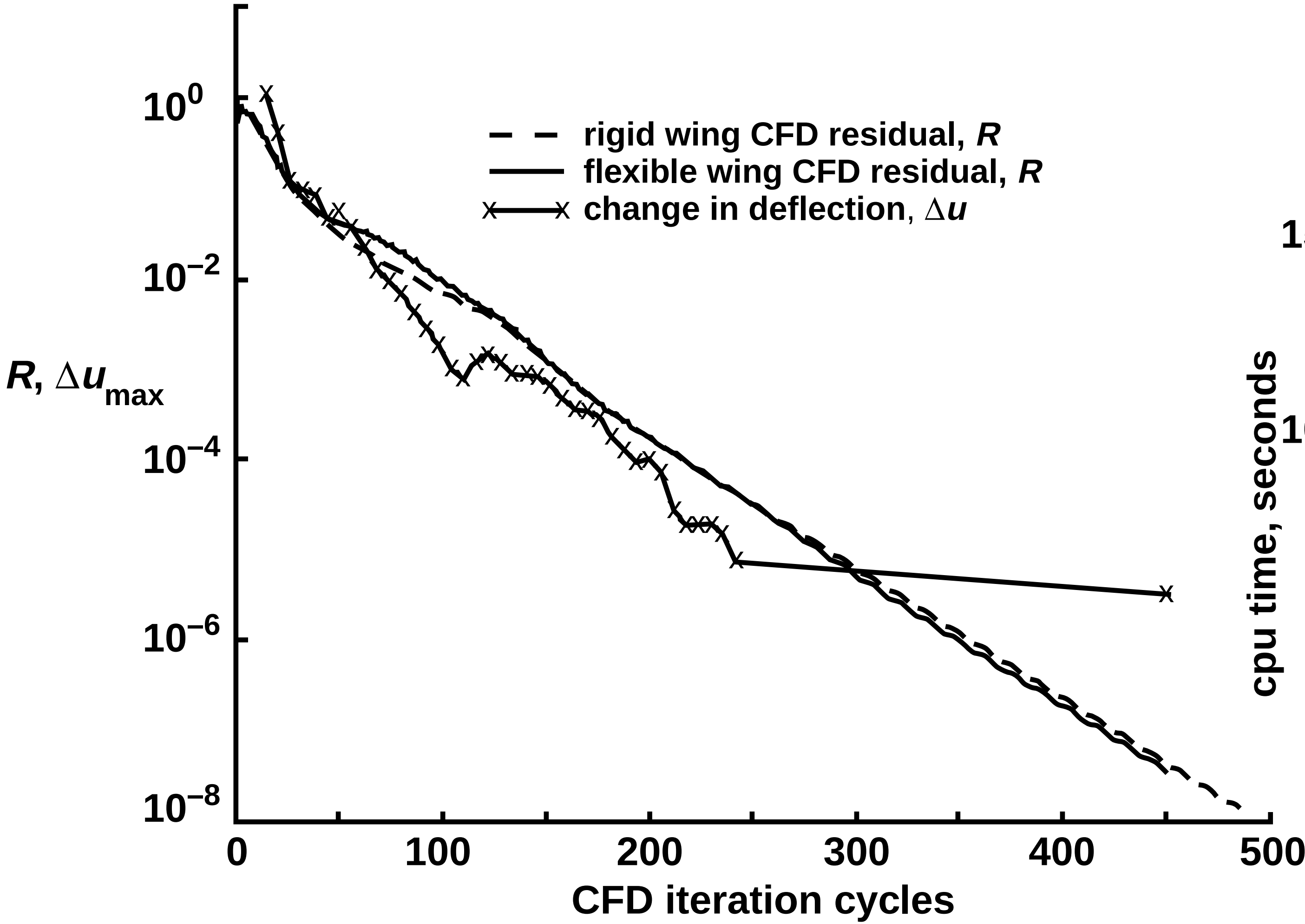
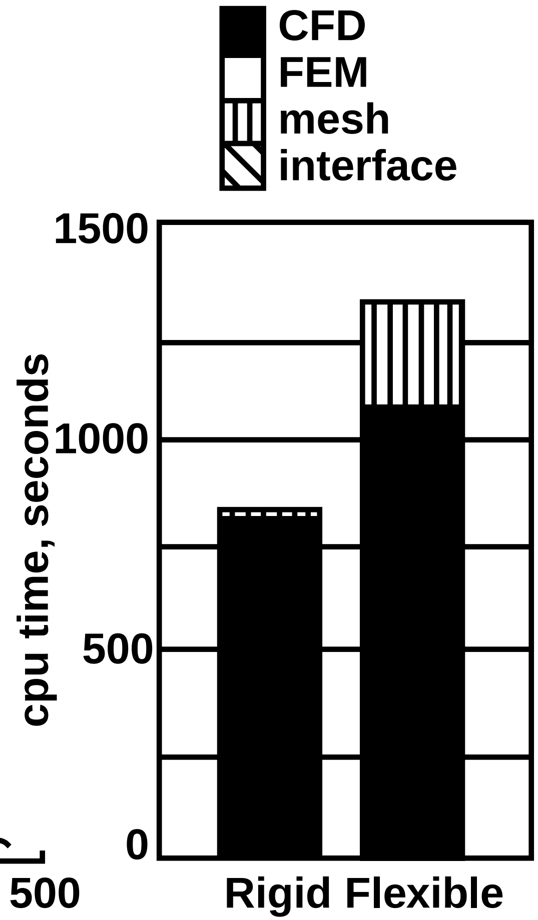
Process Implementation
Aerodynamics / Structures Coupling





Process Implementation
Aerodynamics / Structures Derivative Coupling